Title: Relative Orientation of Binary Spiral Galaxies
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Abstract

Many galaxies, such as our own, contain a large rotating disk of stars, and are labeled spiral galaxies. In order to gain perspective on the formation phenomena, I study the origin of the rotational angular momentum in such galaxies, which presumably points perpendicular to the plane of the disk. The current theory proposes that galaxies gain their rotational angular momentum through tidal interactions with other galaxies and the inhomogeneous environment. If a pair of galaxies constitutes an isolated system at the time of formation, the total angular momentum will remain zero, and the orbital angular momentum will cancel with the sum of the two internal angular momenta. In the simplest scenario, spiral galaxies in an isolated pair with little or no initial orbital angular momentum would spin each other up; therefore, the spin angular momentum vectors of the companion galaxies would point in nearly opposite directions, and their disks would align parallel.

Many studies have utilized statistics of spin orientations in binary galaxies as a tool to investigate the formation process of galaxies; however, the results have been inconclusive, mainly due to small sample sizes. In some of these studies, an apparently significant alignment between the angular momenta of spirals in pairs is found, although these findings sometimes differ (e.g. Helou 1984; Flin 1993; Sofue 1992). I have recently researched the hypothesis of parallel disks in isolated pairs of spiral galaxies using a much larger sample obtained from the Sloan Digital Sky Survey Data Release 6 (SDSS DR6), which contains photometric and spectroscopic information on over 900,000 galaxies. A sample of 747 isolated binary spiral galaxies is compiled by first placing an upper limit on the separation between galaxies in a pair. Further constraints ensure that the pairs in the sample are isolated from other galaxies in the survey. The relative orientations of the pairs are studied, and the result is found to be consistent with a random distribution. No excess of parallel-oriented pairs is found; therefore, I conclude that the simple hypothesis of mutually torqued pairs is inadequate in describing the formation process. The tidal effects of more distant galaxies and of larger-scale structure in the universe must be taken into account.

1. Introduction

A galaxy can be defined as a massive, gravitationally bound collection of stars, gas, dust, and dark matter. The formation process of galaxies in the universe is still not well understood. The problem is that galactic formation is not a brief, well defined process and cannot be observed directly, as the galaxies are extremely far away and we observe only a snapshot of the formation. Thus, indirect methods must be used to gain perspective into the process. One such method is to study properties of present day galaxies that presumably have not changed much since the galaxies formed. A good candidate for such an approach is the spin angular momenta of binary spiral galaxies, as it is hard to coherently change the spin of a galaxy in subsequent encounters. The internal spin is expected to drastically change only in a merger with a galaxy of comparable size.

Luminous galaxies ($M_r < -18$ or so) can be coarsely divided into two classes, conventionally labeled "early-type" and "late-type". Early-type galaxies have redder stellar populations and a scarcity of interstellar gas and dust. The majority of luminous early-type galaxies are ellipticals, which are well described by a de Vaucouleurs profile: $\log I \propto -r^{1/4}$. The majority of luminous late-type galaxies are spiral galaxies, which are well described by an exponential profile: $\log I \propto -r$.

Spiral galaxies, with their thin disks, have likely not suffered a major merger (or a large number of minor mergers) in the last billion years or so, and are therefore attractive targets to study. In other words, these are ordered, low entropy systems for which I expect the spin angular momentum has not undergone drastic changes since formation. Isolated binary spiral galaxies (a pair of spiral galaxies which are relatively close and interact with each other, but are isolated from other galaxies of comparable size) serve as a source of relatively simple systems which can be used to test different theories of galactic formation. For instance, our Galaxy and the Andromeda Galaxy constitute one such pair; although there are numerous other galaxies within the Local Group (which is about 1 Mpc across), our Galaxy and the Andromeda Galaxy are by far the largest and most luminous. Additionally, the third largest galaxy in the Local Group is M33, which is two magnitudes fainter than our galaxy. The relative orientation of these rotationally supported disk galaxies in space can be used to test for an alignment between the angular momenta. In the simple case of an isolated pair of spiral galaxies with no initial orbital angular momentum, interacting through tidal torques, the galaxies would spin each other up. The expected result, from the law of conservation of momentum, is that the spiral disks will align anti-parallel, with angular momentum vectors pointing in opposite directions. However, this conservation of angular momentum does not necessarily imply anti-parallel spins. For instance, the spins could be parallel and the galaxies could orbit around each other in the opposite direction. Additionally, if the galaxies were not isolated at the time of formation, or if they had some initial orbital angular momentum, a simple relation between the spins will not be observed. Thus, I can adopt as my null hypothesis that the orientation of binary spiral galaxies is completely random. The logical alternatives to the null hypothesis are an excess of parallel (Flin 1993), anti-parallel (Helou 1984), or orthogonal (Sofue 1992) alignments. If such effects exist, they will place important constraints on the theories of formation.

Ideally, I wish to study the angle, β, between the spin axes of the galaxies in each pair. If I assume that the spiral galaxy is a disk with spin axis perpendicular to the plane of the disk, there exists an ambiguity in the galactic inclination angle i, or the angle between the normal to the galaxy plane and the observer's line of sight; thus two solutions are possible for the spin axis of each galaxy. A spiral galaxy, when observed at a given inclination, appears as an ellipse defined by a semimajor axis and a semiminor axis. Essentially, although I know the degree of inclination, there exists an ambiguity as to which end of the minor axis is nearer to the observer. The tilt ambiguity must be resolved in order to study β with any degree of accuracy, but the SDSS DR6 does not offer sufficient information on each galaxy to do so for all pairs. For instance, the tilt ambiguity could be resolved for galaxies with well resolved images and strong dust lanes. However, the vast majority of the images obtained from SDSS DR6 are not sufficiently well resolved, and this method would require the additional assumption such as the dust lanes appear at the outer side of the bright spiral arms.

Although it is not possible with the current data to study the three-dimensional orientation of each binary spiral galaxy, I am able to investigate the two-dimensional projected orientations by studying the angle φ between the position angles of the major axes of galaxies in each pair. I first assume that spiral galaxies are perfectly circular disks; therefore, the observed major axis of the galactic image is perpendicular to the spin axis. Additionally, this assumption allows me to use the apparent axis ratio, q_{25}, of the 25 mag arcsec^{-2} isophote as an indicator of the degree to which the galaxy is tilted. The SDSS DR6 data pipeline finds the best-fitting ellipse to the 25 mag arcsec^{-2} isophote in each band; the semimajor axis and semiminor axis of this isophotal ellipse are

A_{25} and B_{25}, respectively. This isophotal axis ratio $q_{25} = B_{25}/A_{25}$ then provides a measure of the apparent galaxy shape at a few times the effective radius. Additionally, the SDSS DR6 provides the isophotal position angle of the major axis (+N through E).

Gott & Thuan (1978) suggest that if galaxies obtain their angular momentum through tidal spin-up, a correlation between the orientations of the spin-vectors of spirals in pairs exists. Compared to a distribution of random orientations, there will be relatively many pairs with parallel and anti-parallel spin-vectors. For this particular model, the distribution of φ offers a more sensitive test than does the distribution of β (Sharp et al. 1979). I observe only the projected orientations of the galaxies, so in principle information is lost; however, for this particular model the expected distribution of φ deviates more from random than the distribution of β does (Oosterloo 1992). Moreover, since the measurement of a spiral galaxy's position angle is much easier to obtain and requires less information than the decomposition of its spatial orientation, more pairs can be used in tests involving φ than in tests with β. This test with φ will however not detect every conceivable deviation from randomness. For instance, if the distribution of β is asymmetric around $\beta = 90^\circ$ as reported by Helou, when folded around $\beta = 90^\circ$ it looks more or less like the random distribution, the test of φ will give that the orientations are random (Oosterloo 1992). However, this method is still useful in determining if there is an excess of galaxies aligned with parallel disk planes. Thus, even without detailed kinematic information, I am able to test the hypothesis of an excess of parallel disk planes.

Alternatively, a subset of my data can be compiled for which the tilt ambiguity is resolved, and therefore I am able to study the angle β between the spin axes. This ambiguity is resolved when pairs are studied for which one member is observed to be nearly edge-on or face-on. Essentially, there is no tilt ambiguity in an edge-on or face-on galaxy; therefore, the ambiguity in the inclination of the second galaxy is unimportant in determining the angle β. In this section I refine my assumption of the galactic shape and consider every spiral galaxy to be a perfect oblate spheroid with intrinsic short-to-long ratio $\gamma = c/a$. This method is utilized in the second section of my study. Additionally, I consider whether the distribution of β depends on the number of large neighboring galaxies.

The idea of comparing the orientation of spiral binaries as a test for the origin of angular momentum is well recognized and has been studied by many. In some of these studies, an apparently significant alignment between the angular momenta of spirals in pairs is found, although these findings are sometimes different. A recent study by Pestaña & Cabrera (2004), in which 46 pairs of galaxies were studied, shows some significance against the null hypothesis of random orientations. Pestaña & Cabrera find that more orientations than expected occur for axes aligned either nearly parallel (spins parallel or anti-parallel) or nearly orthogonal. Flin (1992), using 603 isolated pairs of galaxies in the northern hemisphere obtained from the Karachentsev (1972) sample, finds that the galaxy rotation axes favor a parallel distribution, and avoid being perpendicular. Oosterloo's study (1992) results in a random distribution of orientations amongst the 34 pairs of galaxies observed. Furthermore, Oosterloo finds that the magnitude of the orbital angular momentum of the system is typically a factor 4 larger than the sum of the internal angular momenta of the galaxies in the pair. This is interpreted as an indication that the pairs were not dynamically isolated at the time they formed. He suggests that pairs for which the spin-vectors were correlated had low orbital angular momentum and have merged. The correlation found by Helou (1984) (using 31 pairs of galaxies) is that the distribution of the angle between the two spin-vectors appears to be asymmetric: the spin-vectors tend to avoid being close to parallel and favor being anti-parallel. Sofue (1991), using a sample of 278 pairs of galaxies, finds that the projected directions of the rotation axes of interacting galaxies tend to align orthogonal to each other. Sofue suspects that galaxies aligned parallel (or anti-parallel) would have more easily merged to become a single galaxy due to stronger interactions and dynamical friction.

In Section 2, I describe how I select a sample of SDSS galaxies with exponential profiles to give a population of disk-dominated spiral galaxies. In Section 3 I describe the methods used to select pairs of isolated spiral galaxies, as well as the methods used to analyze the data. Finally, I briefly discuss the results and present my conclusions.

2. **Data**

The Sloan Digital Sky Survey (SDSS) is a project which has surveyed more than a quarter of the sky. Over eight years, it obtained deep, multi-color images and created 3-dimensional maps containing more than 930,000 galaxies and more than 120,000 quasars. A CCD mosaic camera (Gunn et al. 1998) images the sky in five photometric bands (*ugriz*) from the near ultraviolet to the near infrared (Fukugita et al. 1996; Smith et al. 2002). In this paper, I use the *r*-band data, at an effective wavelength of 6165 **Å.** The SDSS Data Release 6 (DR6) includes 9583 square degrees of photometric coverage and 7425 square degrees of spectroscopic coverage. The SDSS DR6 data processing pipeline provides a morphological star/galaxy separation, with extended objects classified as "galaxies" and pointlike objects classified as "stars".

From the SDSS DR6 spectroscopic sample, the primary sample of galaxies is obtained by first selecting objects marked as extended objects. The flux limit of the SDSS DR6 spectroscopic sample is $m_r = 17.77$. According to Hubble's law, the redshift of a galaxy is proportional to its distance from our galaxy; I assume a Hubble constant $H_0 = 70$ km s^{-1} Mpc^{-1} in a flat universe with $\Omega_{m,0} = 0.3$ and $\Omega_{\Lambda,0} = 0.7$. Next, I impose the criterion that the redshift of each galaxy is between $0.004 < z < 0.1$, corresponding to an approximate distance interval of 10 Mpc < d < 400 Mpc and resulting in a low-luminosity cutoff of $M_r = -20.4$. The lower limit on redshift serves to eliminate contaminating foreground objects, and the upper limit reduces the possibility of weak lensing distortions of apparent shapes and eliminates, in practice, the necessity of applying K-corrections. The SDSS DR6 spectroscopic sample provides a measure of the statistical confidence level in each redshift measurement, given as zConf; thus, to eliminate low quality redshifts, I required zConf > 0.35. To ensure that the galaxies in the sample are resolved spatially, I required that their photometric data fulfill the criterion $\tau > 6.25\tau_{psf}$, where τ is the adaptive second-order moment of the galaxy image and τ_{psf} is the adaptive second-order moment of the point spread function at the galaxy's location. Essentially, I want well resolved images because any smearing will affect the projected semimajor and semiminor axes, making the galaxy appear rounder than in reality; thus, I require that the square of the radius of the galaxy be at least $6.25\tau_{psf}$. This primary sample of galaxies contains 166,853 total galaxies.

Using the complete sample of N = 166,853 galaxies, I extract a pure sample of spiral galaxies. The SDSS DR6 pipeline takes the best-fitting de Vaucouleurs model and exponential model for each galaxy, in each photometric band, and finds the linear combination of the two that best fits the galaxy image. The de Vaucouleurs profile is given by:

$$I(R) = I_e exp\left(-7.67\left[\left(\frac{R}{R_e}\right)^{1/4} - 1\right]\right), \qquad (1)$$

truncated beyond $7R_e$ to go smoothly to zero at $8R_e$. The exponential profile is given by:

$$I(R) = I_e exp\left[-1.68\left(\frac{R}{R_e} - 1\right)\right], \qquad (2)$$

truncated beyond $3R_e$ to go smoothly to zero at $4R_e$. In both equations, the variable R_e represents the effective radius of the galaxy, or the radius within which one half of the total luminosity of the system is emitted. The parameter fracDev describes the fraction of the linear combination contributed by the de Vaucouleurs profile. As previously stated, the majority of luminous early-type galaxies are ellipticals which are well described by a de Vaucouleurs profile, while the majority of luminous late-type galaxies are spiral galaxies which are well described by an exponential profile. In a color-magnitude (CM) diagram, if the color index is chosen correctly, the early-type and late-type galaxies manifest themselves as a "red sequence" and a "blue sequence", respectively. Strateva et al. (2001) find an optimal color separator of *u-r* = 2.22, when color alone is used as a discriminator between early-type and late-type galaxies. I adopt the classification of Vincent & Ryden (2005), who find that galaxies with the parameter fracDev ≤ 0.1 on average have a flatter disklike shape corresponding to a spiral galaxy. Previous studies of late-type galaxies in the Sloan Digital Sky Survey have used different definitions of "late-type galaxy". Chang et al. (2006) and Shao et al. (2007), in their studies of late-type galaxies find it useful to choose a sample with fracDev < 0.5. However, Unterborn and Ryden (2008) find that in their full sample of galaxies which have 0.1 < fracDev ≤ 0.5, there are a significant number of galaxies at the faint end of the red sequence (M_r ~ -19.5, *u-r* ~ 2.4), which constitute early-type galaxies. Thus, the criterion that fracDev < 0.5 allows some galaxies from the red sequence to enter the sample. Since the fracDev distribution is strongly peaked at fracDev = 0 (Unterborn & Ryden 2008), I choose to make the more stringent cut fracDev ≤ 0.1 to create my late-type galaxy subsample.

When a spiral galaxy is seen at an arbitrary inclination, it will appear fainter at visible wavelengths than when seen face-on because of scattering of light by the galactic dust. Unterborn & Ryden (2008) find the dependence of dimming on apparent axis ratio to be well fit by the relation $\Delta M_r = 1.27(\log q)^2$. Thus, if a galaxy at arbitrary inclination were observed face-on, the absolute magnitude would be $M_r^f = M_r - \Delta M_r$. A simple flux-limited subsample will be biased against spirals at high inclination due to their lower flux. To correct this, I required any galaxy not already seen edge-on (q ≤ 0.2) to be above the limit if it were seen edge-on. If a spiral galaxy has an observed apparent axis ratio $q_{obs} > 0.2$, the edge-on flux is given by:

$$m_r(edge - on) = m_r(observed) + \Delta M_r(q = 0.2) - \Delta M_r(q_{obs})$$

$$= m_r(observed) + 1.27[(\log 0.2)^2 - (\log q_{obs})^2] \qquad (3)$$

Finally, although the disks of spiral galaxies are known to be well fitted by exponential profiles, so are other subclasses of galaxies, such as dwarf ellipticals. The assertion that exponential galaxies are flattened, dust-containing disks can be tested by studying their colors as a function of apparent axis ratio. If a galaxy is a disk, then its apparent axis ratio *q* will be smallest when it is edge-on; if the galaxy's disk is dusty, then the galaxy will be most reddened when it is observed edge-on. Unterborn & Ryden (2008) find that for exponential galaxies brighter than $M_r \sim -19$, there is a noticeable correlation between *q* and *u-r* at a given absolute magnitude, with smaller values of *q* corresponding to larger values of *u-r*, as expected for a population of dusty disk galaxies. However, at $M_r > -18$, they find no correlation between *q* and *u-r*. At these low luminosities, the galaxies in the sample are blue ($u-r \sim 1.5$) dwarf galaxies in which the stars and dust are not in orderly thin disks. Therefore, in order to eliminate dwarf ellipticals, I further require that $M^f_r \leq -19.4$, as demonstrated by Unterborn & Ryden (2008). Thus, although I do not obtain each possible spiral galaxy in the flux-limited sample, I am confident that my criteria provide a sample of late-type spirals whose light is dominated by a dusty exponential disk.

3. **Data Analysis**

Having compiled a sample of N = 32,358 spiral galaxies, I next select the binary systems from the sample. I require that the projected separation of the galaxies in a pair be no more than 1 Mpc, and that the systemic radial velocity difference between the galaxies must be less than 300 km s^{-1}, to eliminate projected pairs from the true physical pairs. Finally, I require that there are no other galaxies (spirals, elliptical, and irregulars) in the SDSS DR6 spectroscopic sample within a projected separation of 1 Mpc and velocity difference of 300 km s^{-1} of each galaxy in the pair. In order to obtain the two-dimensional physical projected separation from the two dimensional angular separation, I must assume a distance to the pair. I note that although Hubble's law gives an approximation of the distance to the galaxies, it is not reliable in determining the radial distance between two close galaxies in a pair due to their peculiar motions; thus I cannot determine the three-dimensional separation of the pair. To determine the physical separation in two dimensions, I use the angular separation of the galaxies on the night sky, in addition to the mean redshift of the galaxies as a measure of the distance to the pair.

3.1 Method 1

The first portion of my analysis involves studying the angle φ between the projected major axes of the galaxy images in each pair. In this analysis, the cases of parallel and antiparallel spin axes are indistinguishable; however, any finding against the null hypothesis of random orientations in spiral binaries would have implications on the theories of galactic formation. My data consists of pairs of projected major axes for isolated binaries, from which we determine the smallest angle, φ, between the two. I ensure that we obtain the smallest angle by utilizing the following equation:

$$\cos(\varphi) = |\cos(\theta_1 - \theta_2)| \qquad (4)$$

where Θ_1 and Θ_2 represent the isophotal position angle of the major axis of each galaxy in the pair, given by the SDSS DR6 spectroscopic sample. If the disks are randomly oriented relative to each other, then the distribution of φ will be uniform on the interval [0,90˚] (Oosterloo 1992); therefore, the distribution should follow a straight line with unit slope on a cumulative probability plot. Our sample consists of 747 isolated spiral binaries for which the angle between major axes is determined; a histogram of the data is shown in Figure 1. The impression that the distribution presented is isotropic is supported by both the χ^2 test and the Kolmorogov-Smirnov test. I report my results of both tests in terms of the *p* value, which is the smallest significance level at which the relevant hypothesis would be rejected given the observed realized value of the test statistic. I calculated the χ^2 statistic for goodness of fit and obtained a *p* value greater than 0.90. Figure 2 shows a plot of the cumulative distribution of φ, together which the distribution expected from the null hypothesis of random orientations. From Figure 2, the K-S test statistic, D_n is found; a graphical interpretation of D_n is the maximum vertical distance between the two cumulative probability distributions. For the given data, I obtain a K-S test *p* value of 0.89. Thus the observed distribution of φ is consistent with being drawn from the parent distribution dictated by the null hypothesis.

In order to ensure that the galaxies in my sample are unbiased with respect to inclination, I compared the ratio of the semi-major and semi-minor axes (*q*) of each individual galaxy in my sample of pairs to a sample of N = 15,088 isolated spiral galaxies. In order for a galaxy to be considered isolated, there cannot exist another galaxy (from SDSS DR6 spectroscopic sample) within a projected separation of 1 Mpc with a velocity difference less than 300 km s^{-1}. As *q* is an observed quantity, it is my best choice for making such a comparison. The cumulative probability distributions of the two samples are shown in Figure 3. The application of a K-S test to the distributions rendered a *p* value of 0.060; thus, the two distributions appear consistent with being drawn from the same parent population.

Finally, I study the effect of the projected separation between the binary galaxies on the angle φ. A plot of φ versus the projected radius of separation is shown in Figure 4. The distribution appears random, and no trends emerge with decreasing R_{sep}. Therefore, I conclude that the projected radius of separation alone had little or no effect on the distribution of φ. I speculate that if a trend were to emerge in the distribution, it would not vary drastically over the range of 1 Mpc for the projected radius of separation. However, upon loosening my constraints and increasing the allowed projected separation of galaxies in a pair to 5 Mpc, I still do not observe any obvious trend in the data. Furthermore, I conjecture that the surrounding neighborhood, particularly the density of neighboring galaxies and interstellar dust contained within it, would more greatly influence the pair of galaxies than their projected separation.

3.2 Method 2

Method 2.1

The second method involves studying the angle β between the spin axes of the galaxies in each pair. However, this analysis can only be performed unambiguously on binary systems with at least one face-on or one edge-on member; also, I must assume that galaxies are oblate spheroids. If every spiral galaxy were a perfect oblate spheroid with intrinsic short-to-long axis ratio $\gamma = c/a$, then the inclination *i* would be uniquely determined by the apparent axis ratio *q*, through the usual relation

$$\cos^2 i = \frac{(q^2-\gamma^2)}{(1-\gamma^2)} \qquad (5)$$

Unterborn and Ryden (2008) find the median dimensionless disk thickness for their sample of spiral galaxies to be $\gamma \approx 0.22$; I adopt this convention for my study. In the case of an observed galaxy with $q < 0.22$, cos i is assumed to be zero.

Therefore, I first compile a sample of binaries with an edge-on galaxy, and a sample of binaries with a face-on galaxy. The convention adopted was that a galaxy with $q \leq 0.3$ was considered edge-on, and a galaxy with $q \geq 0.9$ was considered face-on. In the case of a pair with an edge-on galaxy, the angle β is determined by

$$\cos\beta = \sin i\,|\cos\varphi| \qquad (6)$$

where i is the inclination of the galaxy not observed to be edge-on, and φ is as previously defined. In the case of a pair with a face-on galaxy, the angle β is given by

$$\cos\beta = \cos i \qquad (7)$$

where i is the inclination of the galaxy not observed to be face-on. If a pair consists of one face-on and one edge-on galaxy, then Equation 6 is utilized. If instead Equation 7 were utilized in this scenario, I would observe an excess of binary systems with $\cos\beta = 0$.

My data consists of values of φ and q for N = 265 pairs of galaxies, from which I calculate estimates of β. As demonstrated by Pestaña and Cabrera (2004), in the case of a uniform distribution on the three-dimensional sphere, cos β has a uniform distribution on the interval [0,1]. Figure 5 shows the cumulative probability distribution of cos β for pairs with an edge-on galaxy and pairs with a face-on galaxy, along with the distribution of cos i for isolated galaxies to serve as a reference. I do not observe a uniform distribution as expected due to my assumptions about the intrinsic shape of spiral galaxies. For instance, the distribution of cos i for does not begin at the origin because of my assumption that any spiral galaxy with an observed axis ration $q < 0.22$ has an inclination given by cos $i = 0$. Additionally, the distribution does not culminate at a 45˚ angle at (1,1) because of the assumed aspect of oblateness for each spiral galaxy. Nonetheless, these inaccuracies resulting from my assumptions hold for all of my observations, and will not affect my final results. Therefore, in practice I compare my distributions not to a straight line, but rather to the distribution of inclinations for isolated spiral galaxies. The distribution of cos i for isolated galaxies represents the distribution of the tilt relative to the line of sight. In the case of a binary system with a face-on galaxy, the distribution of cos β similarly represents the distribution of the tilt of the second galaxy in the pair relative to the line of sight. In the case of a binary system with an edge-on galaxy, the scenario is identical, except that reference is rotated by 90˚. Therefore, if the null hypothesis and my various assumptions are correct, I expect the distribution of cos i for isolated galaxies to match the distribution of cos β for the binary spiral galaxies.

The cumulative distribution of cos β is given in Figure 5, together with the distribution of cos i for isolated galaxies that is expected for random orientations. In comparison to the distribution expected from the null hypothesis, a K-S test of the pairs containing edge-on and face-on galaxies rendered p values of 0.37 and 0.29 respectively. In comparison to each other, the pairs containing edge-on and those containing face-on galaxies return a p value of 0.82. Thus, all three distributions are consistent with being drawn from the same parent population. Although not statistically significant, the figure shows that there is a slight preference for isolated binary spiral systems containing an edge-on or face-on galaxy to be aligned with orthogonal disks.

To further analyze the data, I compare the distribution of q for partners of edge-on and face-on galaxies to that of the isolated galaxy sample, as shown in Figure 6. A K-S test of the distribution of q found for partners of edge-on and face-on galaxies in comparison to that of isolated galaxies rendered p values of 0.14 and 0.40 respectively. In comparison to each other, the distribution of cos i for partners of edge-on and face-on galaxies returned a p value of 0.71. This implies that the assumptions used in the construction of Figure 5 are suitable for my study, as the distributions are similar. Additionally, the figure demonstrates that there is a slight tendency for both the partners of edge-on and face-on galaxies to be edge-on. Once again, these results are not statistically significant.

Method 2.2

Finally, as an extension to my second method, I investigate the effect of the pair's neighborhood on the distribution of β. For each pair of galaxies, I determine the number of neighbor galaxies within a projected radius of 5 Mpc having a relative systemic velocity within 300 km s^{-1} of either galaxy in the pair. In order to be considered a neighbor, the galaxy must also be equally as bright as, or brighter than the dimmer of the two galaxies in the pair. As luminous spiral galaxies have comparable mass to light ratios, the luminosity is related to the mass of a galaxy; thus, the second requirement ensures that neighbors are approximately as large as, or larger than the smaller galaxy in the pair. I choose this criterion because I assume that only neighbors of comparable mass to the galaxies in the pair will have a significant effect on the relative orientation of the two. The median number of neighbors was found to be six and was used as a discriminator to obtain a high-density and low-density subsample. In other words, pairs with six or less neighbors constitute the low density subsample, while those with more than six neighbors are considered in the high-density subsample.

There are some interesting differences between the two subsamples, but in general they give equivalent results. As with the previous study, I first examine the distribution cos β in comparison to the distribution of cos i for isolated spiral galaxies. Figures 7 and 8 show these distributions for the low-density and high-density subsamples, respectively. In the low-density subsample, a K-S test of the data returned a p value of 0.68 for pairs with an edge-on galaxy and 0.57 for pairs with a face-on galaxy when compared to the distribution obtained from isolated spiral galaxies; in comparison to each other, a p value of 0.85 is found. In the high-density subsample, a K-S test of the data compared to the distribution obtained from isolated spiral galaxies returned a p value of 0.25 for pairs with an edge-on component and 0.10 for those with a face-on component; in comparison to each other, a p value of 0.52 is obtained. The pairs of galaxies in the high-density subsample, especially those which contain a face-on galaxy, seem to have a greater tendency toward orthogonal alignment when compared to the sample of isolated galaxies.

As with the previous study, I next investigate the distribution of q for partners of edge-on and face-on galaxies to that of the isolated spiral galaxy sample; figures 9 and 10 show these distributions for the low-density and high-density subsamples, respectively. In the low-density subsample there is not a significant deviation for either set of partners when compared to the sample of isolated galaxies. The p values rendered from a K-S test are found to be 0.16 for partners of edge-on galaxies and 0.47 for partners of face-on galaxies when compared to the isolated spiral galaxies. However, in comparison to each other, a *p* value of 0.05 is obtained. The partners of edge-on galaxies in the low-density subsample slightly favor an edge-on orientation, while the partners of face-on galaxies slightly favor a face-on orientation. The high-density subsample reveals some more interesting and puzzling results in that there is a much greater tendency for partners of face-on galaxies to be observed edge-on. In comparison to the sample of isolated galaxies, the partners of face-on galaxies yield a *p* value of 0.046, while the partners of edge-on galaxies yield a *p* value of 0.34. In comparison to each other, the distributions of partners of edge-on and face-on galaxies return a *p* value of 0.40. It is not immediately apparent as to why these two distributions differ as so. Nonetheless, the sample of face-on partners is inconsistent with the null hypothesis at the 95% level and favors an edge-on orientation. Additionally, I varied the projected radius of separation criterion for the neighbors only to obtain similar results.

4. Conclusion

I have studied the angle φ between the projected major axes of 747 binary spiral galaxies, as well as the angle β between the projected spin axes of 265 binary spiral galaxies. In contrast to others, I find that there are no indications for a coupling between the orientations of the spin-vectors for spiral galaxies in pairs. However, my study utilizes a much larger sample size than most of the other work done on the subject, and serves as a useful beginning for further research. Although some interesting trends do emerge, they are mostly not statistically significant. I find that the distribution of the angle φ, as well as the angle β, is consistent with the null hypothesis of random orientations. When the neighborhood of the galaxies in considered, and the sample is split into a low-density and a high-density subsample, slightly varying results are obtained; it is worth further investigating the mechanism behind these results. If possible, it would also be beneficial to study the relationship between the internal spin angular momenta and the orbital angular momentum of each pair of galaxies. For instance, Oosterloo (1992) suggests that pairs for which the spin-vectors were correlated had low orbital angular momentum and have merged. Additionally, Sofue (1991) conjectures that parallel-spinned galaxies would have more easily merged to become a single galaxy due to stronger interaction and dynamical friction. Nonetheless, the tidal effects of more distance galaxies and of larger-scale structure in the universe must be taken into account in order to reveal the mechanisms underlying galactic formation.

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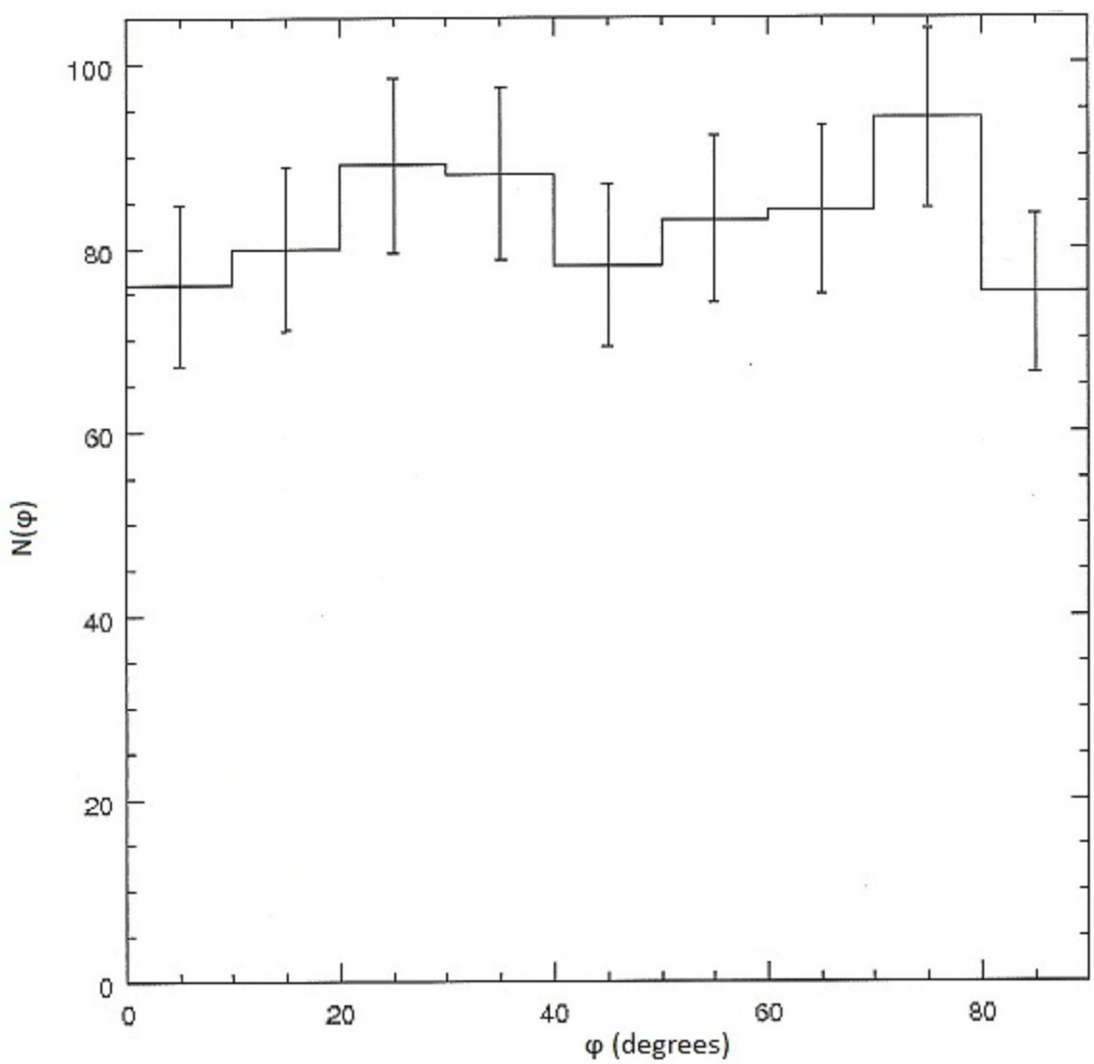

Figure 1 – A histogram which represents the distribution of the angle φ between major axes of the full sample of 747 isolated binary spiral galaxies.

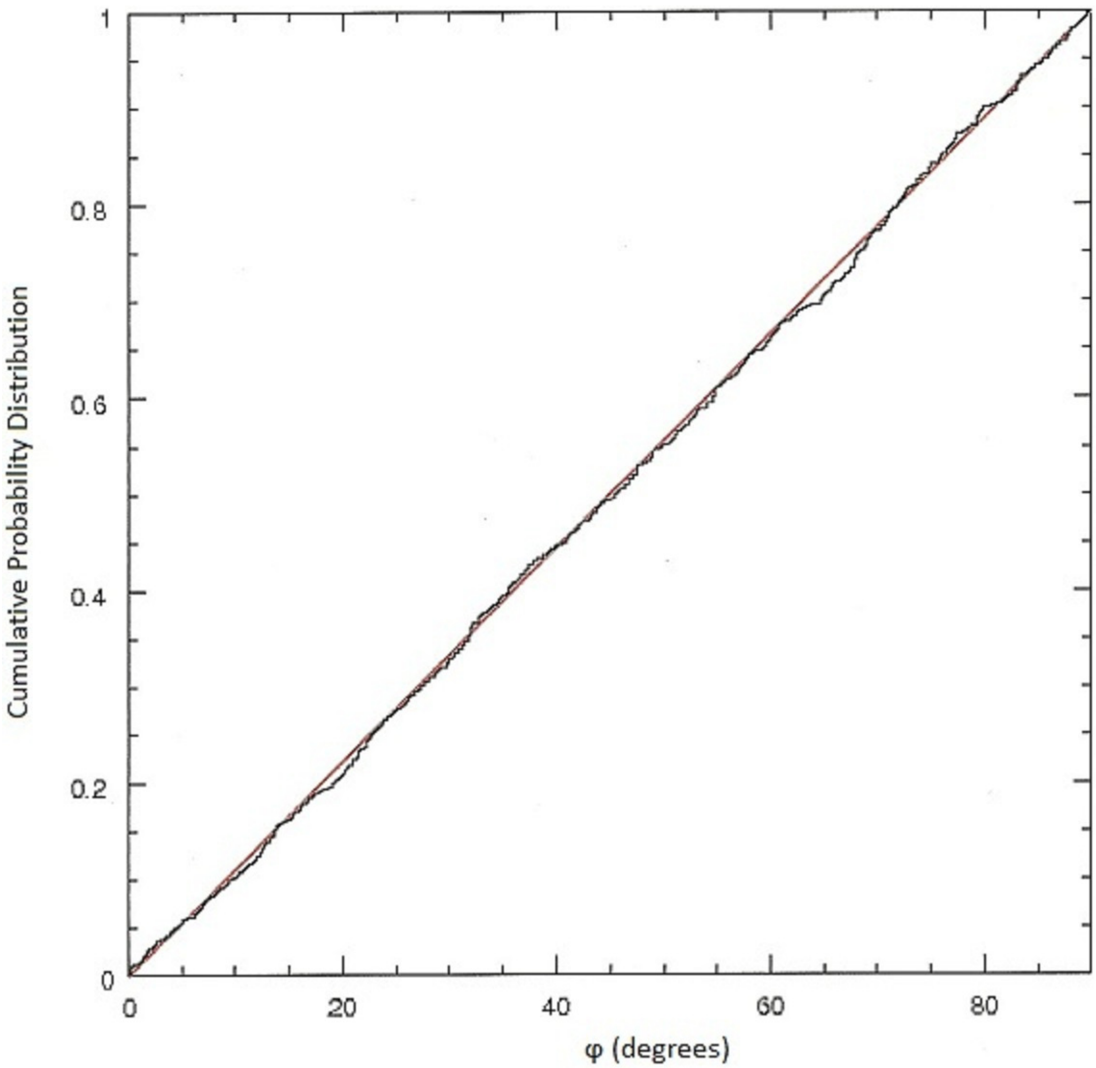

Figure 2 – A cumulative probability distribution of the angle φ between major axes in my full sample of 747 isolated binary spiral galaxies.

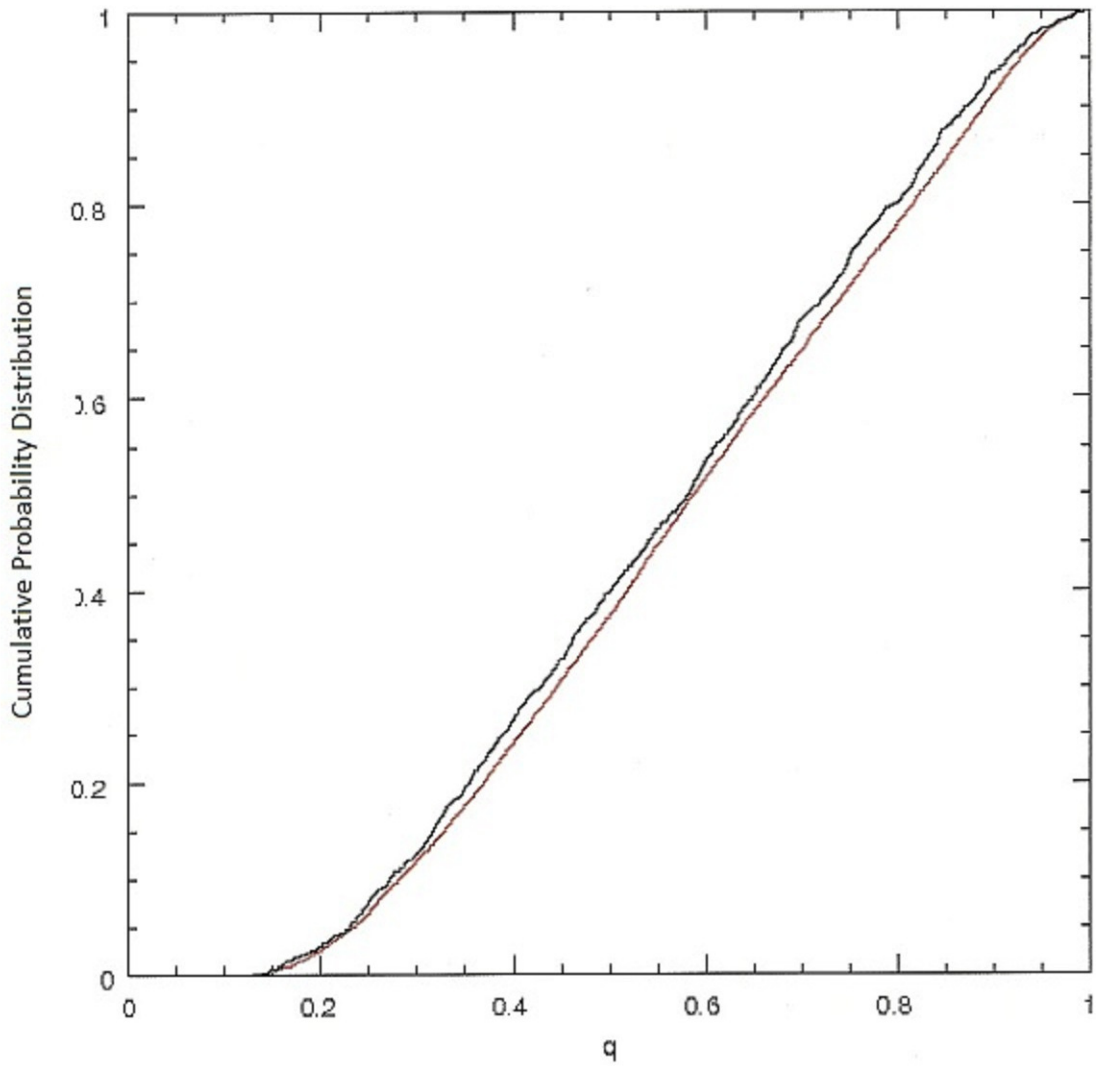

Figure 3 – A cumulative probability distribution of the apparent axis ratios of each individual galaxy in my sample (black) compared to that of isolated spiral galaxies (red)

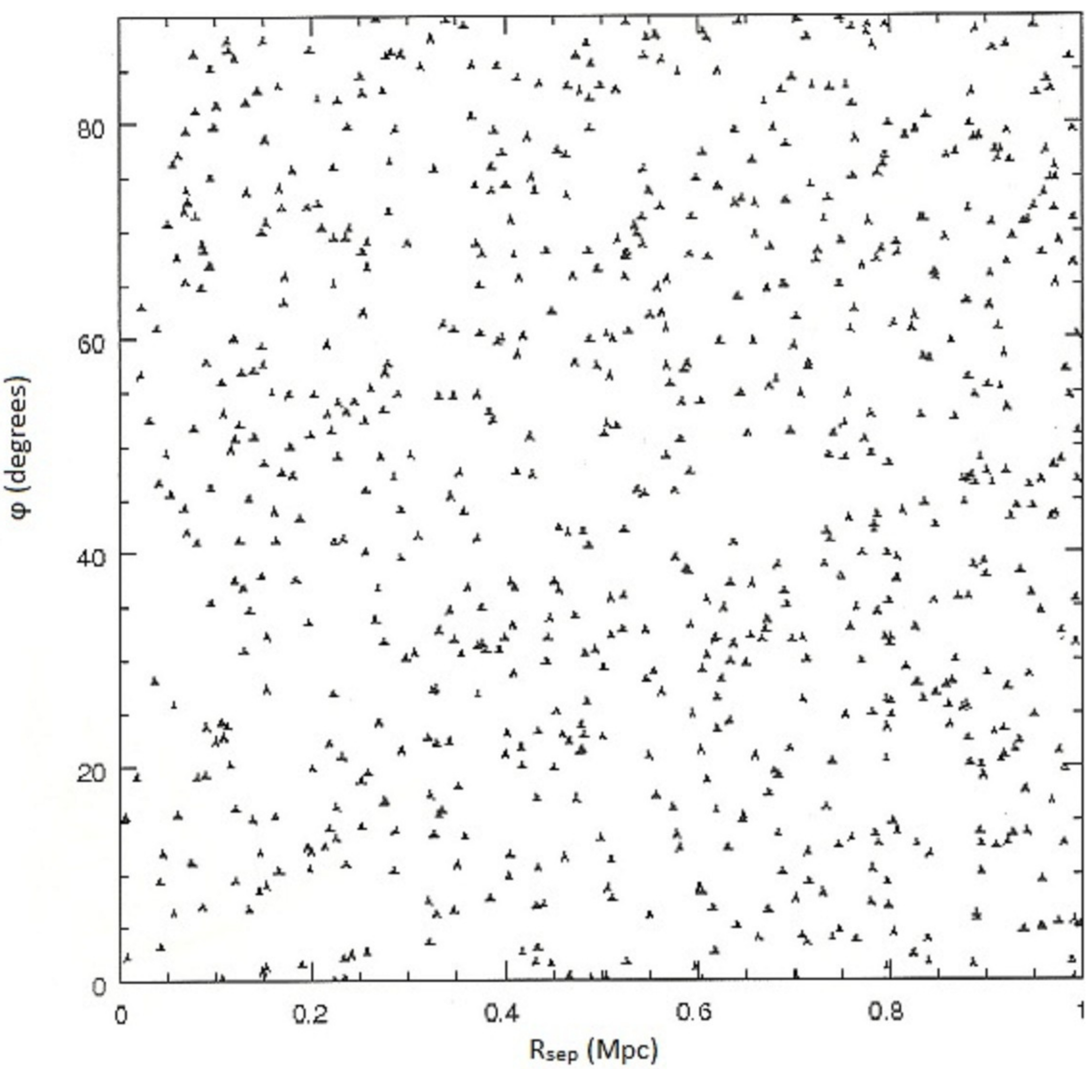

Figure 4 – A plot of the angle φ between major axes in my full sample of 747 isolated spiral binary galaxies versus the two-dimensional projected radius of separation.

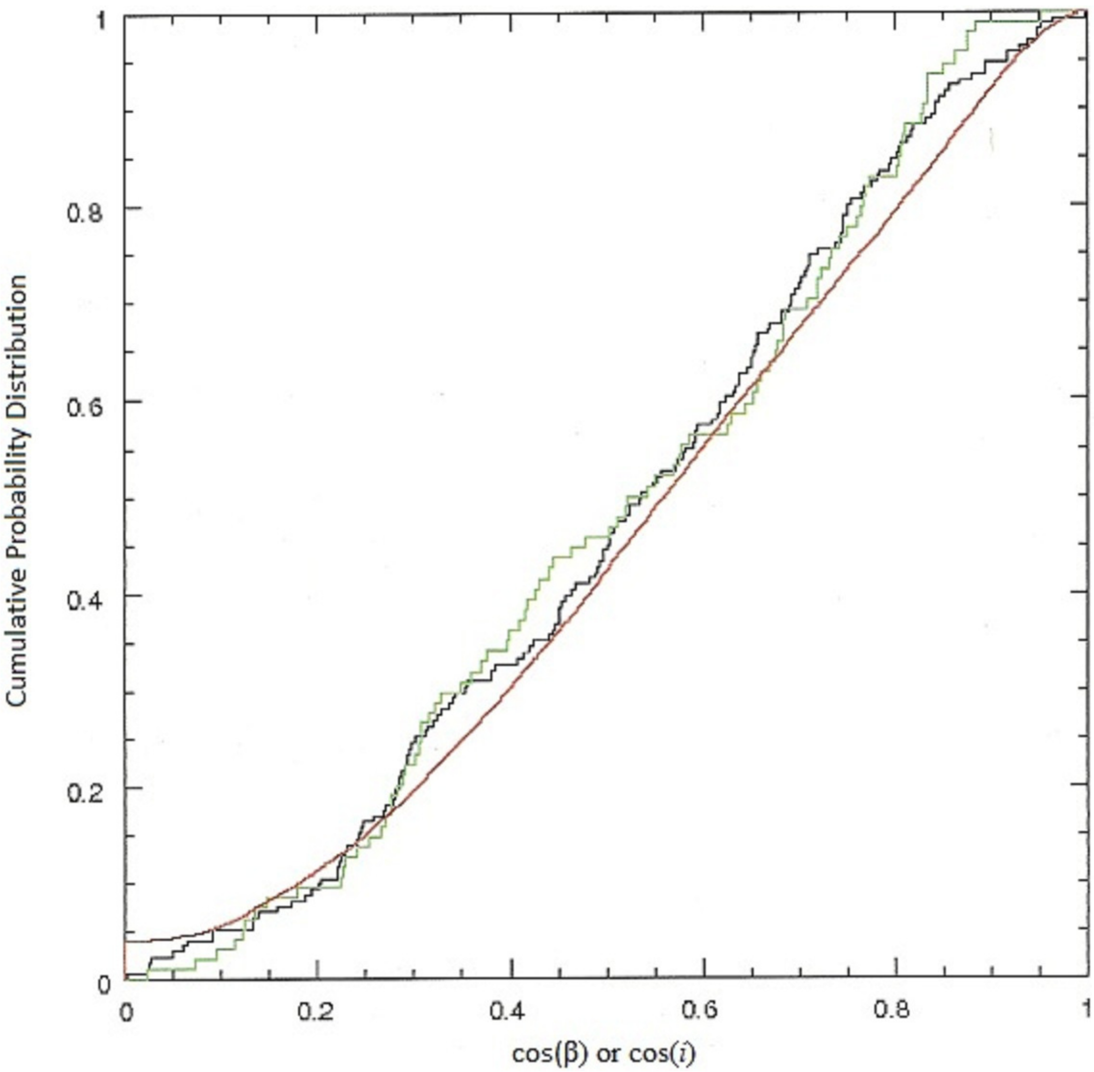

Figure 5 –A cumulative probability distribution of cos β for isolated spiral binary galaxies containing an edge-on (black) or face-on (green) component together with the distribution of cos *i* for isolated spiral galaxies (red).

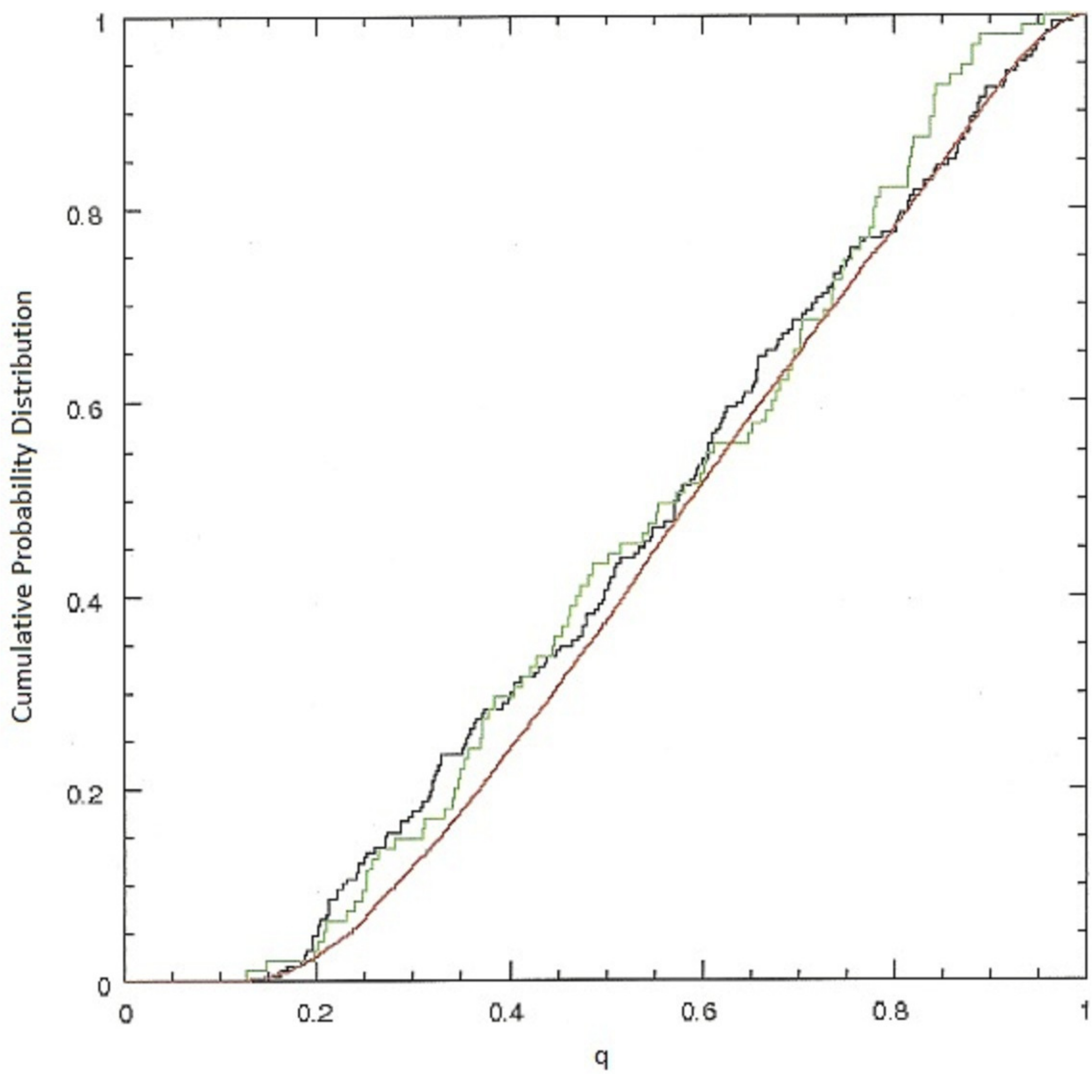

Figure 6 – A cumulative probability distribution of the apparent axis ratio for partners of edge-on galaxies (black), partners of face-on galaxies (green), and isolated spiral galaxies (red).

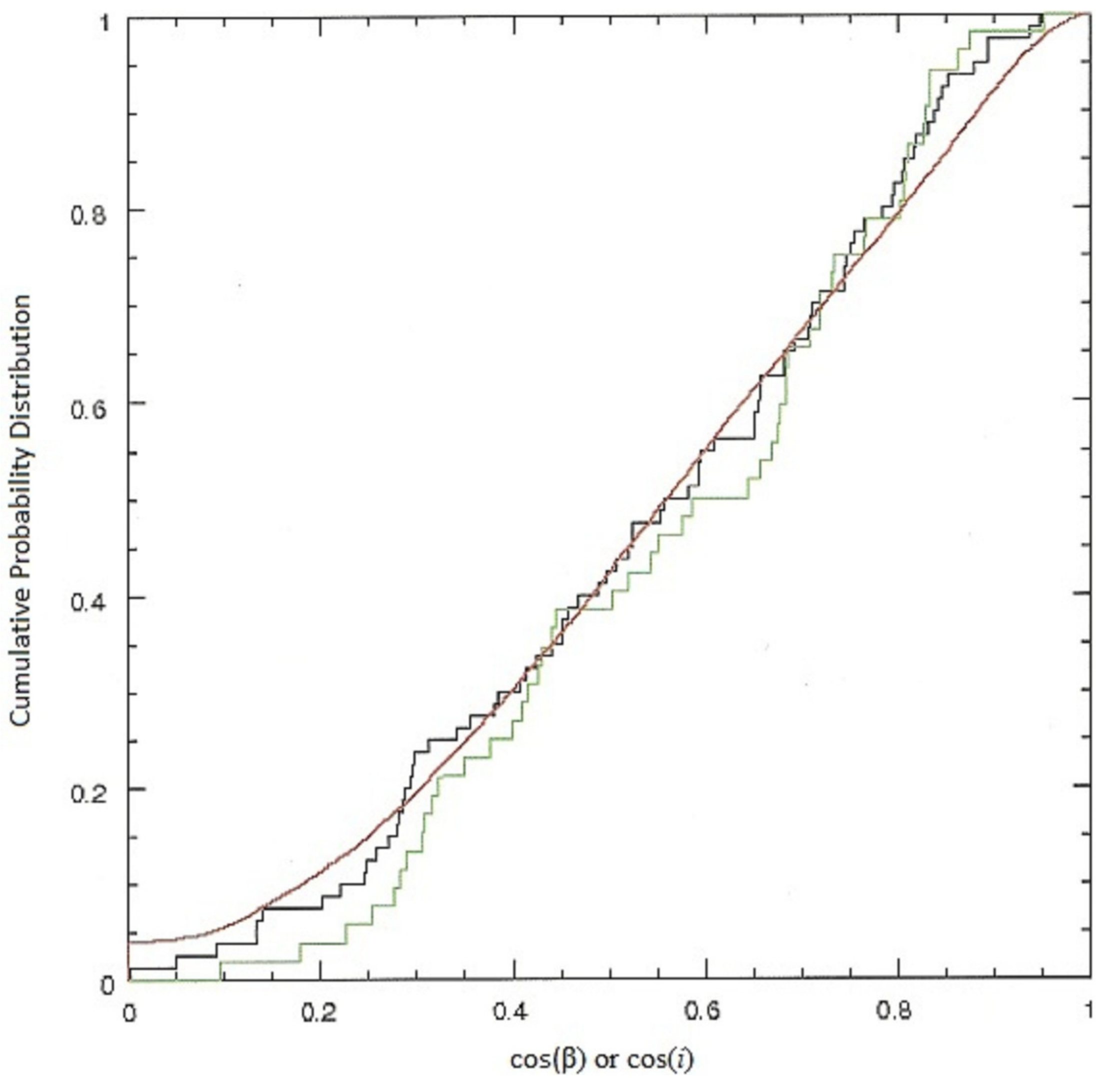

Figure 7 - A cumulative probability distribution of cos β for isolated spiral binary galaxies containing an edge-on (black) or face-on (green) component in the low-density subsample together with the distribution of cos *i* for isolated spiral galaxies (red).

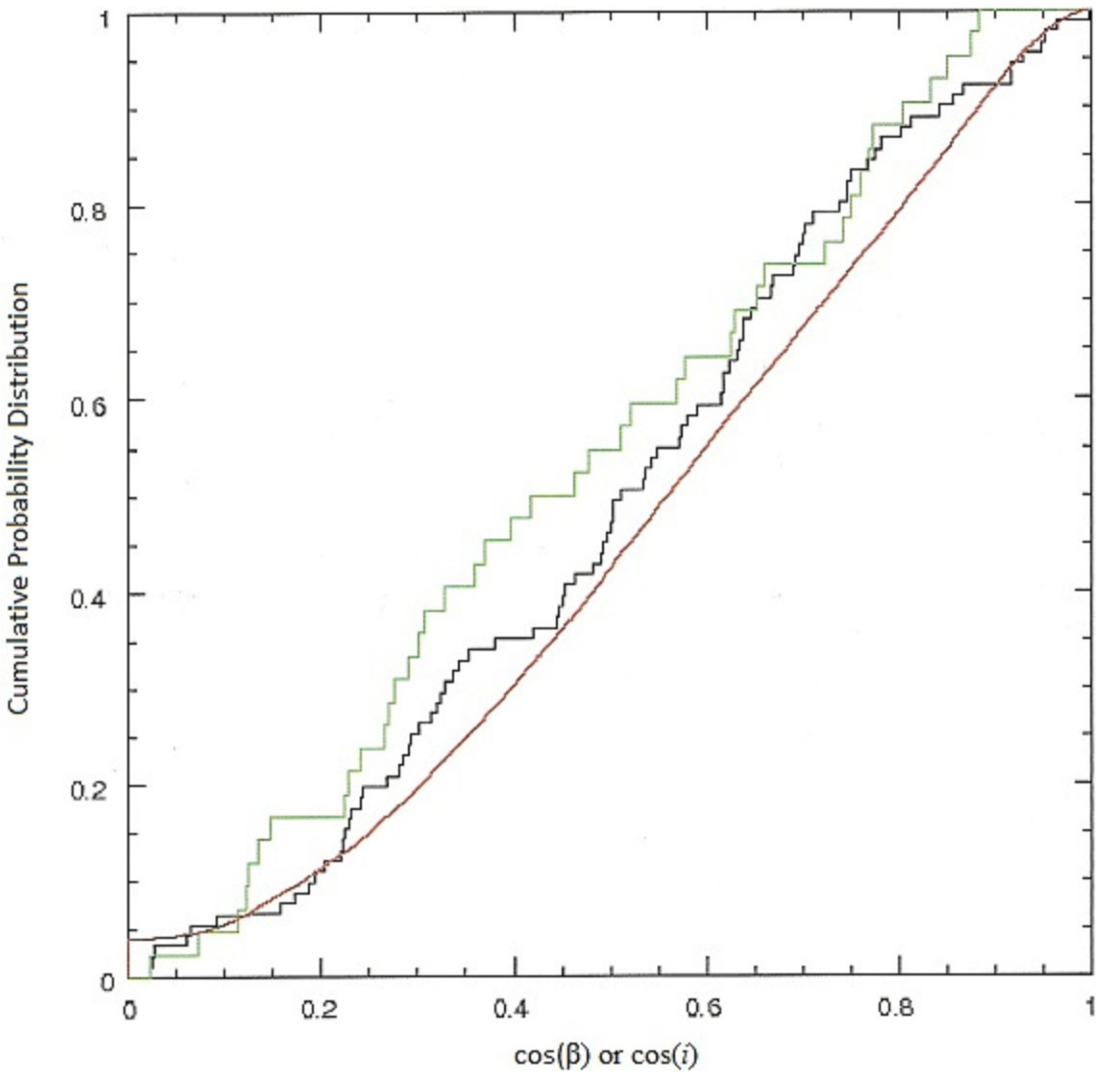

Figure 8 - A cumulative probability distribution of cos β for isolated spiral binary galaxies containing an edge-on (black) or face-on (green) component in the high-density subsample together with the distribution of cos *i* for isolated spiral galaxies (red).

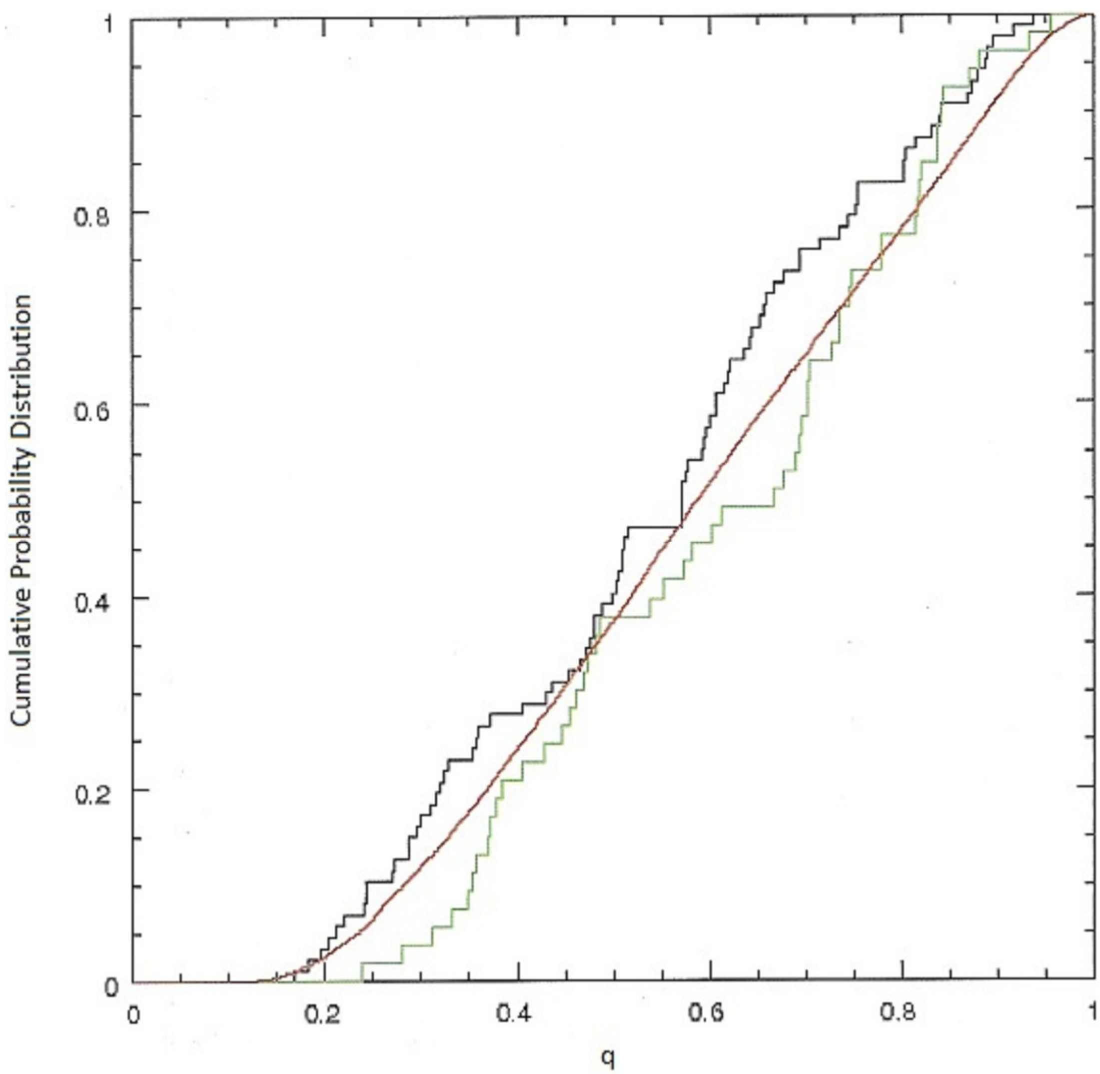

Figure 9 - A cumulative probability distribution of the apparent axis ratio for partners of edge-on galaxies (black) and partners of face-on galaxies (green) in the low-density subsample, as well as the distribution for isolated spiral galaxies (red).

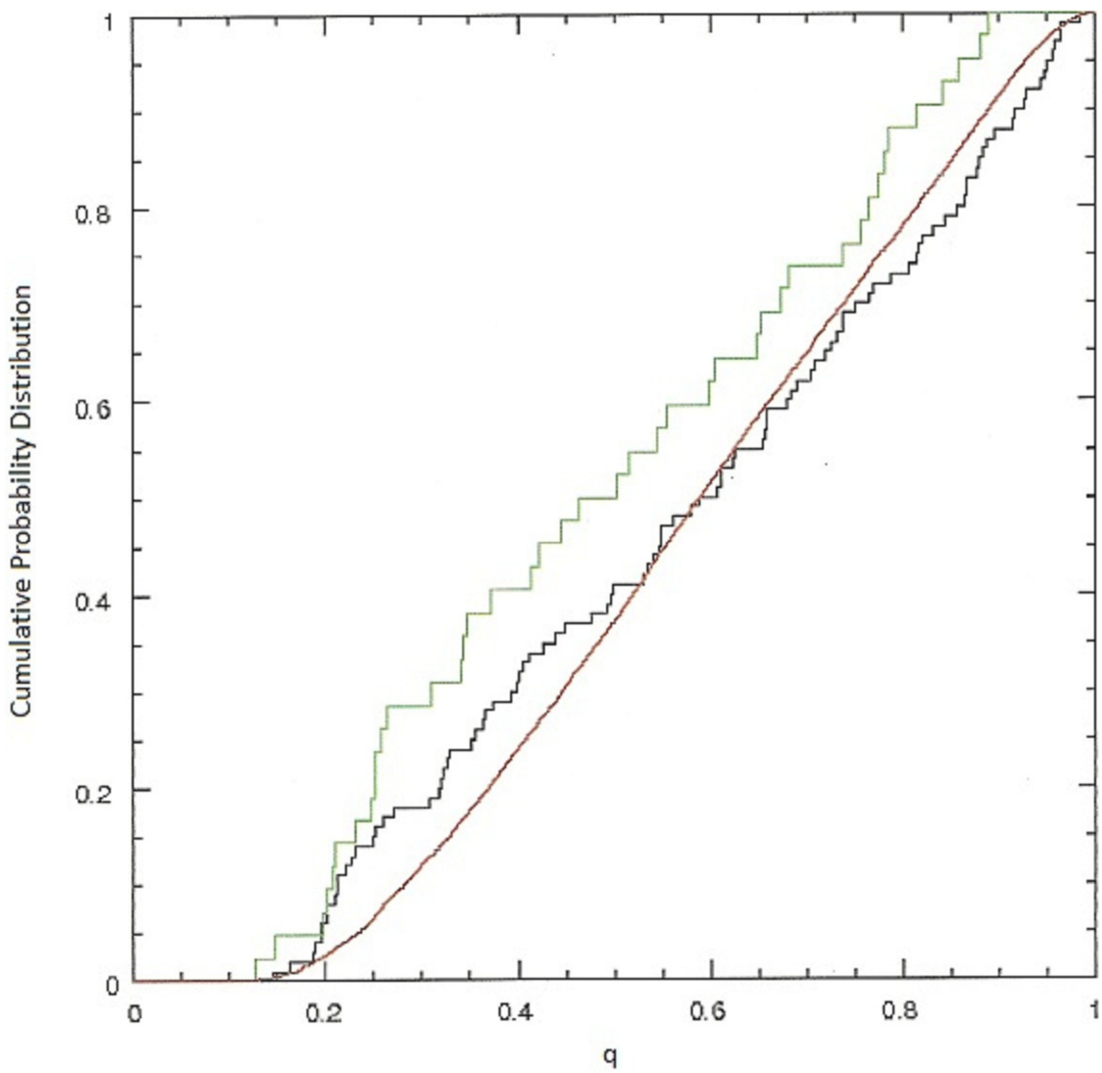

Figure 10 - A cumulative probability distribution of the apparent axis ratio for partners of edge-on galaxies (black) and partners of face-on galaxies (green) in the high-density subsample, as well as the distribution for isolated spiral galaxies (red).